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Using Unmanned Air Systems to Monitor Methane in the Atmosphere

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February 2016

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Abstract

Methane is likely to be an important contributor to global warming, and our current knowledge of its sources, distributions, and transport is insufficient. It is estimated that there could be from 7.5 to 400 billion tons carbon-equivalent of methane in the arctic region, a broad range that is indicative of the uncertainty within the Earth Science community. Unmanned Air Systems (UASs) are often used for combat or surveillance by the military, but they also have been used for Earth Science field missions. In this study, we will analyze the utility of the NASA Global Hawk and the Aurora Flight Sciences Orion UASs com- pared to the manned DC-8 aircraft for conducting a methane monitoring mission. The mission will focus on the measurement of methane along the boundaries of Arctic permafrost thaw and melting glaciers. The use of Long Endurance UAS brings a new range of possibilities including the ability to obtain long-term and persistent observations and to significantly augment methane measurements/retrievals collected by satellite. Furthermore, we discuss the future of long endurance UAS and their potential for science applications in the next twenty to twenty-five years.

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1 Introduction

Global warming likely caused by human activity is a recent phenomenon. The amount of methane in the atmosphere has significantly increased and this has become an increasing threat to the delicate heat balance of Earth. Our understanding of the contribution of atmospheric methane to climate change is limited and it is crucial that we learn more about the sources of methane so that we can better formulate a way to stabilize or end the increasing release of methane. With increased knowledge, there can be increased general awareness of the issue, which in turn, will cause a greater focus on the issue of methane gas in the atmosphere. The amount of methane trapped in permafrost that is being released every year due to climate change induced thaws is unclear, but we do know the amount trapped in the ice is far larger than our atmosphere can absorb without significant effects on global average temperature.

Permafrost is defined as perennially frozen ground that remains at or below zero degrees Celsius for two or more years [8]. It generally forms in regions where the mean annual temperature is colder than zero degrees Celsius and underlies approximately twenty two percent of the earth's land surface [9]. Assessing methane emissions is difficult due to the lack of reliable estimates and data collected in the arctic regions. The amount of methane hydrates in the permafrost is estimated to range from 7.5 to 400 billion tons of carbon-equivalent [10]. This large range illustrates the uncertainty that surrounds methane in the permafrost. The origin of the methane, however, is well understood. Methane hydrates are a type of clathrate compound, a polymeric lattice structure that traps or contains another molecule—in this case, methane [11]. Methane clathrate, or methane hydrates, are composed of methane gas frozen into ice, formed at cold temperatures and under high pressure, conditions that are found in the permafrost and under the ocean floor [10]. As the earth's temperature rises, melting occurs, releasing the trapped methane [11]. This process can, however, be inhibited by the presence of ice in the permafrost region above the destabilized clathrate as long as the permafrost is not completely melted [11]. The zones where the permafrost is melting are currently the area most critical for this study, and as such, we have focused on the Mackenzie River Delta on the border between Alaska and Canada.

The concept for this campaign is to make detailed measurements of methane concentrations over an extended period of several months using remote sensors mounted on an UAS. The Mackenzie Delta, including offshore undersea regions, is overlain by a thick layer of permafrost trapping known deposits of gaseous hydrates that contain very large quantities of methane. This region is the target of much exploratory drilling for the purpose of commercial extraction of natural gas. Drilling activities plus natural seepage eventually leads to significant emissions of methane that need to be accurately quantified. Since the seepage can be from point sources, an intensive search pattern should be flown to pinpoint releases. This region is chosen to illustrate the concept of operations, but any similar region of interest can be targeted using the sampling strategy described in this report.

1.1 The Importance of Methane

Methane, CH_4, is one of the most potent "greenhouse gases", meaning it traps infrared radiation (heat) emitted from the earth's surface and increases the surface temperature. Without greenhouse gases, however, life on Earth as we know it would not be possible; the earth would be too cold to support human life. The issue is, most likely, as a result of human activity, the concentration of gases in the atmosphere have increased to levels that are having an effect on global average temperature sufficient that global warming has become a concern.

Currently, CH_4 concentrations are 2.5 times greater than that of the pre-industrial atmosphere

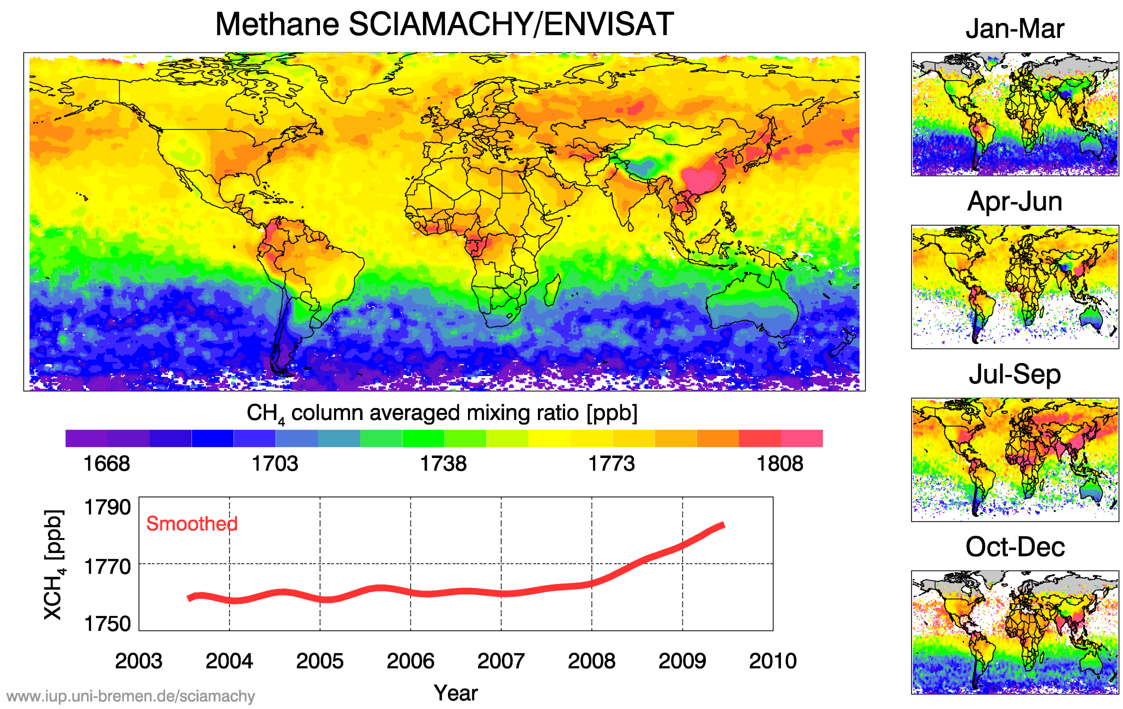

Figure 1. Methane Distribution in the Atmosphere calculated from Satellite Measurements of Reflected and Backscattered Solar Radiation Spectral Data [1]

[12]. In 2013, methane "accounted for about 10% of all U.S. greenhouse gas emissions from human activities" [13]. Globally, over 60% of all methane emissions are caused by humans [13].Other sources of methane include, but are not limited to: wildfires, wild animals, vegetation, and wetlands [14]. The mean lifetime of methane molecules is only about 12 years in the atmosphere before the methane is disassociated. During that time, however, it causes the equivalent warming of 28-36 years of carbon dioxide equivalent [13]. The relative impact of CH_4 on global warming is 25 times greater than CO_2 over a 100-year period [13]. Additionally, the oxidation of methane by hydroxyl radicals in the troposphere leads to the formation of formaldehyde, carbon monoxide, and ozone [12]. These chemicals also affect the concentration of water vapor and ozone in the stratosphere [12]. The listed effects emphasize that methane is far more effective than other greenhouse gases in absorbing the Earth's emitted heat and thus causing a temperature increase. The process of releasing methane hydrates becomes a positive feedback loop increasing the rate of melting making it possible that a runaway release of methane may occur.

Figure 1 was made using data from the SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) image spectrometer onboard the European environmental satellite ENVISAT within a methane retrieval algorithm developed by the University of Bremen [1]. ENVISAT ("Environmental Satellite") is an inoperative satellite that provided measurements between March 2002 and May 2012. The methane retrieval algorithm compares light coming from the sun to the light reflected by the Earth, which provides information on trace gases and aerosols in the atmosphere through which the Earth-reflected light has passed. Fig. 1 shows the annual and seasonal mean total column methane retrieved from ENVISAT data. Closer inspection of local methane maxima shows several areas of interest: the rice fields in China, African tropics, and Siberia (in the summer months). During the July to September period in Siberia, there is a significant increase in methane release into the atmosphere relative to the other seasons, which is

likely due to methane hydrate release from thawing permafrost. This area in Siberia is estimated to account for as much as 70 billion tons of methane, a quarter of all the methane stored on the land surface of the world [15]. The Mackenzie Delta permafrost has become the focus of our studies, however, because our access to Siberia is restricted and it is difficult to reach with a long endurance unmanned air system from the United States due to the distance.

1.2 Why UAS Observations?

This methane mission is designed to collect spatially and temporally detailed observations that cannot be provided by the current set of satellites that provide methane data. UAS are also able to fly more frequently and are able to make continuous observations, therefore, making it possible to track the thaw of the methane hydrates. Although satellite sensors are able to provide a wide, global coverage, they have long repeat cycles. With UAS, we can have diurnal observations, repeated as required, and we can better observe biogenic signals at fine spatial scales. Passive sensors on satellites can provide swath coverage but have limited sensitivity in the lower troposphere and at high latitudes, especially near the Mackenzie Delta location. Passive sensor data is highly susceptible to bias from aerosol and cloud contamination. In contrast, an active sensor can be placed on a UAS for high accuracy data at night or during the day, in all seasons and at any latitude. UAS missions comprising of active and passive sensors allow for long duration intensive observations of key trace gases in targeted areas. UAS missions can provide diurnal, monthly, and annual measurements of methane in regions with both natural and anthropogenic emissions. This also allows us to link satellite and surface observations due to increased sensitivity in the lower troposphere. With this proposed mission, we can use the UAS methane data to help calibrate and validate other satellites instruments. Having both active and passive sensors allows for high accuracy and precision methane measurements along with observations of other key trace gases: CO_2, CO, and H_2O that aid in the classification of emission sources.

1.2.1 Current and Future Satellite Observations Currently, NASA does not have an active methane monitoring satellite. Japan's GOSAT (Greenhouse Gases Observing Satellite), or "Ibuki", is one satellite making methane observations since its launch in January of 2009 [16]. It has produced a large number of high-resolution spectroscopic observations using reflected sunlight [16]. As described previously, SCHIAMACHY was a satellite with a spectrometer that provided data from 2002 to 2012. Another satellite launched into orbit in 2002, the Atmospheric Infrared Sounder, AIRS, is an infrared spectrometer on the Aqua satellite that can detect a number of gas species, including CO_2 and CH_4 [12, 17]. Infrared Atmospheric Sounding Interferometer (IASI) and TES (Technology Experiment Satellite) are other satellites with similar qualities to AIRS [17, 18]. IASI was carried by the European Operational Meteorology platform, launched around 2002 and TES was part of the Earth Observing System (EOS-Chem1) that would provide long-term data sets for Earth system Science [18]. Both instruments recorded atmospheric spectra using Earth's thermal emissions [18]. TES was dedicated to chemistry and climate research while AIRS and IASI were the next generation for weather forecasts [17, 18].

Future satellites that may enhance methane measurement data include GOSAT-2, CarbonSAT (Carbon Satellite), TROPOMI (Tropospheric monitoring instrument) on the Sentinel-5 Precursor mission, and MERLIN (Methane Remote Sensing LIDAR).

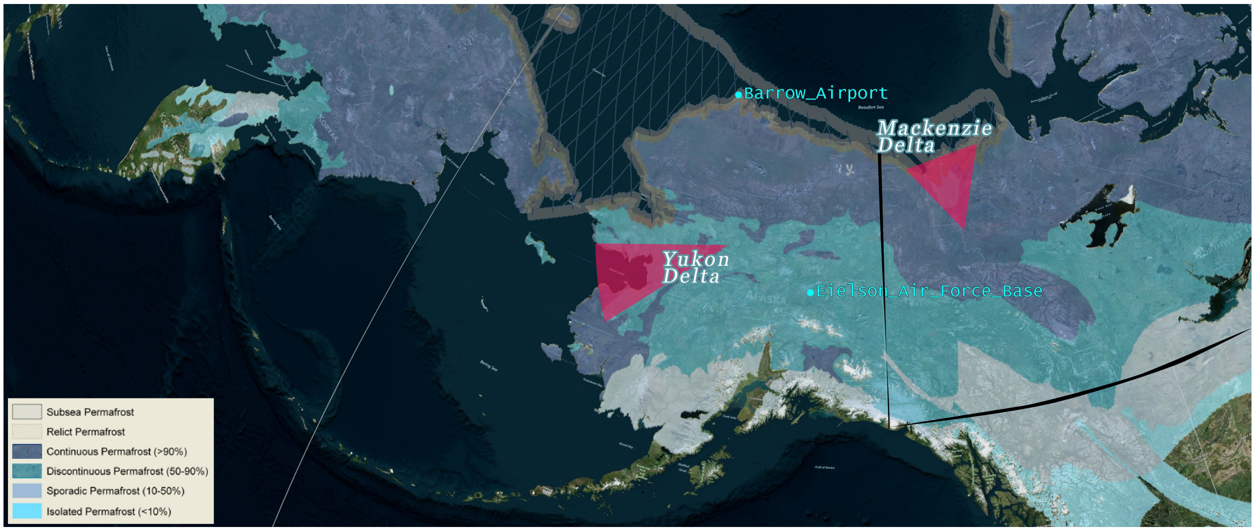

Figure 2. Map of Arctic Permafrost displayed in Systems Tool Kit retrieved from the National Snow and Ice Data Center [2].

1.3 Mackenzie Delta

The map in figure 2 shows the two important landmarks for UAS use in the Alaskan arctic region and western Canadian territory. Both the Yukon River delta and the Mackenzie River delta are within reasonable reach of Eielson Air Force Base (Eielson AFB), one of the bases that these missions could be flown from. For this mission, the Mackenzie Delta will be the primary focus for the following reasons: the Mackenzie Delta has large amounts of methane stored in inland permafrost regions, and even more methane hydrates stored in offshore shelves; there is increased activity in oil and gas production in that area (the primary source for the keystone pipeline in the United States); the Mackenzie Delta has a potential for significant methane emissions due to the surface thawing. The thawing is indicated by the small patch of lighter blue near the border of Alaska and Canada.

2 Campaign Requirements & Objectives

1. The proposed campaign is focused on the growing/thawing season during the late spring into early fall: May to October. It would consist of monthly flights, each making use of the maximum UAVs endurance. As the temperatures begin to warm seasonally and the days become longer, the snow and permafrost begin to melt. In the longer term, as the ocean temperature increases, it causes sub-sea hydrates to thaw.

2. NASA manned aircraft and UASs suitable for this campaign are based at Edwards Air Force Base/Armstrong Flight Research Center in Edwards, California. This makes Edwards one of the main places to consider as a base. Eielson Air Force Base near Fairbanks, Alaska is another base of interest. Although Eielson Air Force Base is much closer to the site of interest, a long term mission such as the one proposed would require a six month relocation of all ground-crew that are required to be present, including a subset of the science PIs for all instruments, and the ground operations station for take-off and landing.

3. The sample region of interest should be flown over at a constant altitude above 20 kft, using

a grid pattern with a desired spacing of about 6 nm. This sample region should contain land of the Mackenzie Delta, as well as some over ocean flight paths to measure the ocean methane hydrates' emissions.

4. Two sensors would be preferred. The primary sensor for this mission is a LIDAR and the secondary sensor is a passive spectrometer. The spectrometer requires daylight and a ground view unobstructed by clouds in order to take measurements.

5. Fly on clear days or days with minimal cloud during daylight by preference, but continue through the night when UAS endurance permits (LIDAR can measure at night, spectrometer requires reflected sunlight).

6. The UAS is controlled and monitored via Iridium satellite links that have 100% coverage in all regions, including the poles.

7. The sensors can be sent commands (if necessary) and monitored via Iridium at low data rates (a few kb/s).

8. All data from the sensors must be recorded onboard the UAS for later retrieval. Minimal data may be sent over the Iridium link to confirm all instruments are working throughout the duration of the mission. Data can also be sent over a KU-band satellite link at up to 25 mb/s but the link is less reliable at high latitudes and is unusable above 70 degrees latitude.

3 Sensors

The sensors consist of a LIDAR and passive spectrometer using reflected sunlight. At this time, no in-situ sampling from the UAS is envisioned. Ground level samples could be taken or sampling from a manned aircraft to complement and confirm the remote sensing measurements. In addition some fights could be timed to coincide with an overpass of a satellite with methane measurement capability for comparison. Measurements are to be made over an extended time period between May and October on a monthly basis. This favors basing the UAS at Edwards or Wallops for logistics and cost reasons. The penalty is a 4200 nm round trip to the region of interest that substantially reduces time and distance on station. Eielson Air Force Base is an option for basing the UAS closer to the region of interest, but is more suited to a shorter duration campaign rather than a campaign that extends over many months. This is because a mobile ground station and operations crew would need to be located at Eielson for the duration of the campaign.

The spectrometer envisioned in this campaign could have traits similar to the the GreenHouse Observations of the Stratosphere and Troposphere (GHOST) instrument [19]. For the purposes of designing a flight mission, the GHOST instrument was baselined. The H2O, CH4, and HSRL Airborne LIDAR Observations(H3ALO) LIDAR system is baselined as the active remote sensor for remote methane measurements [20]. The methane LIDAR is currently being built at NASA Langley Research Center and is designed for operation on manned and unmanned aircraft.

4 Vehicles

4.1 Vehicle Comparison

The aircraft that we've selected for this mission will either be Medium Altitude, Long Endurance (MALE) or High Altitude, Long Endurance (HALE). MALE can fly up to 30,000 feet, whereas

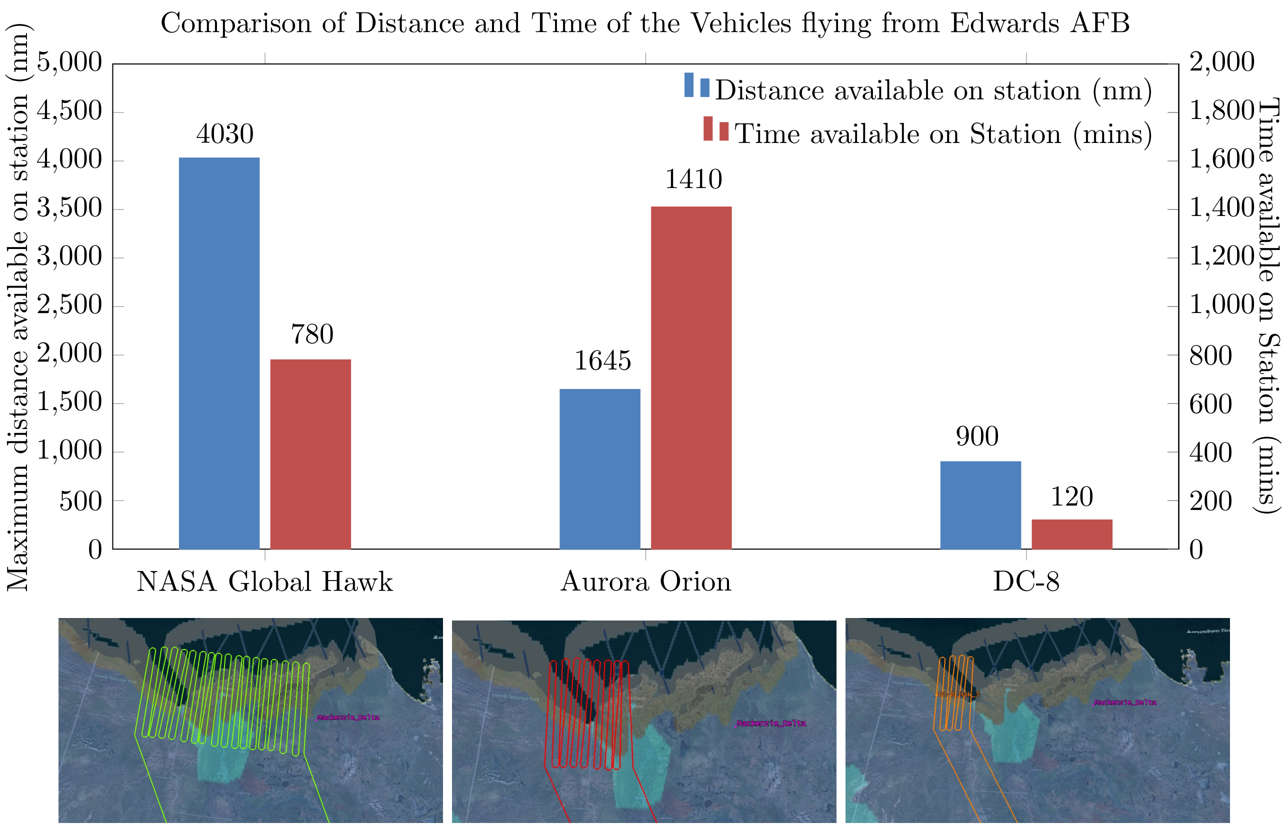

Figure 3. Comparison of On-Station Coverage Capabilities of Study Aircraft [3–5]

HALE UAS fly over 30,000 feet. In this study we compare Northrup Grumman' Global Hawk HALE with Aurora Flight Sciences' Orion MALE and a DC-8 manned aircraft.

In figure 3, the superior range of the NASA Global Hawk is evident. However, the time spent on station by the Aurora Flight Sciences' Orion, is twice the amount of time of the Global Hawk. The DC-8 is significantly inferior to both the UASs in terms of time or distance on station.

4.2 NASA Global Hawk

Currently, NASA owns six Global Hawks. However, only one is currently operational. The Global Hawk has the ability to carry large payloads for an extended period of time. Its thirty-one hour endurance coupled with its 1500 lb payload at max endurance makes it the favored choice on paper, but the reality is that the NASA Global Hawk can fly at maximum endurance with no more than 850 lbs of payload, about the weight of one single instrument. Additionally, due to the payload capacity of the Global Hawk, both instruments were designed for the same compartment and would require reconfiguration before implementing the mission. The NASA Global Hawk has a nominal cruise speed of 310 knots and a max speed of 350 knots. Its nominal cruise altitude is 55,000 feet. It burns about 470 pounds of fuel per hour, which is reasonable for a UAS and far less than a DC-8.

4.3 Aurora Flight Sciences' Orion

Aurora Flight Sciences' Orion is a MALE UAS that is in development. It is advertised with a 8,400 nm flying range at a low speed of 70 knots, ideal for observations, but a disadvantage for long transits to the site. The LIDAR and the infrared spectrometer will be able to get accurate readings with the slower speed because the sensors the measurements can be integrated (averaged) over a long time period. Additionally, Aurora Flight Sciences advertises the Orion as being designed to have low operating costs and an open architecture improving accessibility of the aircraft. Although the aircraft is still in the prototype phase, it is not considered to be a "future aircraft" due to its near-term availability. Aurora Flight Sciences advertises its fuel burn at an extraordinary low 42 pounds per hour, verified by flight test.

Aurora Flight Sciences also claims that the vehicle can be operated by one pilot from the ground station, although two would be used for redundancy, and the operator does not need to be a qualified pilot.. In contrast to Global Hawk, Orion does not require a large crew for the aircraft. The Aurora Orion can house both of the sensors in its payload but its endurance will be impacted if it is carrying both sensors due to the large weight. If there is only one sensor on-board, the Aurora Flight Sciences' Orion has the potential to fly for the full 120 hours that it is designed for.

4.4 Alternative Vehicles: DC-8

An alternative concept of operation for comparison with the UAS is to use a suitable manned aircraft, based at NASA Armstrong/Edwards. The chosen aircraft is a DC-8: with the range of upwards of 5,700 nm, it has the capacity to fly to the Mackenzie area and spend around 900 nm on station before having to return. With a cruise speed of 450 knots, the plane is able to reach the delta in around 5 hours and spend around 2 hours on site. This craft typically has eight crew members to operate and consumes far more fuel than any competing UAS. It is, however, large and is able to hold both sensors with ease and also carry a whole science team to analyze the data on-board. As a manned aircraft, it has the advantage of being able to operate in Federal Air Space with few restrictions. Although operating in the National Air Space is still problematic for UAS, it is more feasible in remote regions, such as the Mackenzie Region.

4.5 Wind and other Issues

Limiting factors for operating a UAS are weather and wind restrictions.

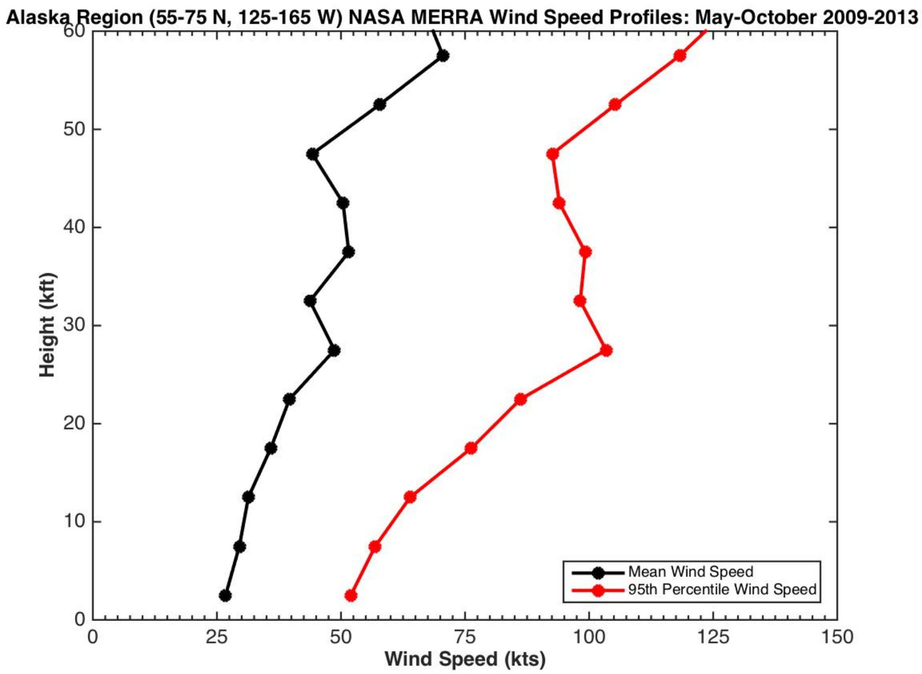

Figure 4. Winds Speed Profiles for the Study Region

Fig 4 shows that winds could be a significant issue for a low speed UAS. Additionally, the spectral imager requires the use of reflected sunlight in Alaska in order to operate. It cannot be used at night or when it is cloudy. Although the Global Hawk can fly above most of the weather and is generally unaffected by it, the LIDAR and spectral imager cannot observe through clouds so the team would need to plan for a few clear days in a row. Due to the slow cruise speed of the Orion, the team must prepare for and predict four or five days of low winds which may be hard to achieve.

On the other hand, due to the high latitude, there are many hours of sunlight during the summer which is conducive to making measurements with the spectral imager if there are more than two clear days to fly per month.

5 Future Vehicles

As this mission is intended as a model for future missions, we looked forward to see what future aircraft could be suited to the proposed mission. The ideal vehicle would be able to fly at various altitudes, have a large payload of 2000 lbs, and have a fast cruise speed to get to its target location quickly before slowing down and making detailed observations with its sensors. Furthermore, it needs a multi-day endurance.

5.1 Boeing Phantom Eye

Figure 5. Boeing Phantom Eye Unmanned Air Vehicle [6]

The Boeing Phantom Eye is a hydrogen fueled, HALE concept aircraft designed for surveillance. It is designed to fly at higher than 60,000 feet and have a 7-10 day endurance with a 2,000+ lbs payload and a cruise speed of 150 knots. Currently Boeing needs substantial funding in order to proceed with the project and build another demonstrator aircraft.

5.2 General Atomics Aeronautical Systems' Predator B ER (NASA Altair)

The General Atomics' Predator B ER is advertised as a HALE/MALE aircraft at a lower altitude of up to 50,000 feet and a 42 hour endurance. It has a maximum internal payload of 850 lbs and a cruise speed of 240 knots. The Altair technology-demonstration variant was developed by General Atomics for NASA.

Figure 6. General Atomics Altair Extended Range Unmanned Air Vehicle [7]

5.3 Advantages and Disadvantages of UAS

The biggest advantages of UAS is that they have long endurances with useful payloads. In the case of the NASA Global Hawk, it has about 31 hours worth of endurance and the Aurora Flight Sciences' Orion has a five day endurance, much longer than most manned airplanes. UAS can operate autonomously once the flight path has been planned. Furthermore, Aurora Flight Sciences claims that the Orion can use its on-board intelligence to adjust the flight trajectory to avoid hazardous weather, which is useful because there can be many uncertainties with planning weather five days in advance. The NASA Global Hawk has a slightly less advanced system that allows it to detect and avoid obstacles through human interaction and control. Most UAS, if not all, are able to take off, land, and do en-route operations autonomously and do not require piloting skills. This also allows for a smaller crew to operate. Aurora Flight Sciences claims that the Orion will

be operable by one or two crew and those operators can be stationed anywhere. That means that there is also no flight crew risk or risk of fatigue. There are also no hour limiters besides the fuel capacity. Because of the autonomous capabilities of these UAS, there are also no safety problems associated with flying at night.

In contrast, the greatest disadvantages of UAS is the smaller payload than large manned aircraft and long endurance UASs generally fly much slower than manned aircraft. Although the Global Hawk has a reasonable cruise speed of 310 knots, the Aurora Flight Sciences' Orion has a slow cruise speed of 70 knots. This means that the Orion cannot be stationed in high winds. Due to the larger wingspans, UAS tend to be less robust to turbulence and other hazardous conditions and cannot take off with a crosswind greater than 15 knots. Lastly, FAA restrictions on flying in controlled air space currently require a certificate of authorization (CoA) on a case-by-case basis.

6 Cost Analysis Based at Edwards

All costs are the authors' initial estimates and not actual values except where sources are listed. Table 1 shows relative performance used in the cost analysis.

	NASA Global Hawk (1 Sensor)	**DC8 (2 Sensors)**	**Aurora Flight Sciences' Orion (2 Sensors)**	**Aurora Flight Sciences' Orion (1 Sensors)**
Transit Time Round Trip (Hrs)	12	9	64	60
Time on Station (Hrs)	15	3	20	60
Distance On Station (nm)	4000	1000	1300	4000
Distance On Station (Ratio)	1	4	3	1

Table 1. Comparison of Vehicles of Interest

6.1 NASA Global Hawk

When calculating the mission total cost in table 2, we calculated this for a term of six months with one flight per month. The assumptions we made were that each flight was to be 27 hours which equals 162 hours total for the campaign. The NASA Global Hawk uses 470 lbs per hour and the fuel cost is calculated from the average fuel cost of Jet A Fuel in the Edwards Air Force Base area in California. The costs for modifications, integration and test reflect the proprietary interfaces and systems that must be changed and tested.

Global Hawk (1 sensor)		
Cost Item	**Value**	**Totals**
Monthly fee (source 2015 NASA Call Letter)	$250,000	$1,500,000
Flight hour rate (source 2015 NASA Call Letter)	$1,800	$291,600
Total fuel cost (included in hourly rate)	$34,093	
Science data communications costs		$42,000
Project management/ requirements/ design/ planning		$300,000
Global Hawk mods assumed to only involve new equipment pallets, mounts, wiring, etc.,		$300,000
Integration and test		$200,000
Flight test		$30,000
Science team total cost (8 scientists @ 160k per year each)		$640,000
Total Direct Costs (NASA rates)		**$3,303,600**

Table 2. Cost estimates of the NASA Global Hawk

6.2 Aurora Flight Sciences' Orion

When calculating the mission total cost in table 3, the assumptions we made were that it would fly for 6 months, and it requires 3 flights per month to cover the same ground as the Global Hawk, making a total of 18 flights for the campaign carrying two sensors. The total number of flight hours per flight is 84 which makes a total 1,512 hours total for the campaign. For a fair comparison with Global Hawk that can only carry one sensor, Orion carrying one sensor requires only 1 flight to cover the same ground as the Global Hawk making a total of 6 flights for the campaign, with costs in table 4. The total number of flight hours per flight is 120, resulting in a total 720 hours total for the campaign. The Orion only uses 42 lbs of fuel per hour. The cost of fuel is calculated from the average fuel cost of Jet A fuel in the Edwards Air Force Base area in California. The costs for modifications, integration and test are less than Global Hawk, since interfaces and systems are non-proprietary and designed in a modular way for ease of integration of payloads.

Aurora Orion (2 sensors)		
Cost Item	**Value**	**Totals**
Flight hour rate (estimate)	$1000	$1,512,000
Total fuel cost assumed included in hourly rate	$28,435	
Science data communications costs		$42,000
Project management/ requirements/ design/ planning (assume same as GH cost)		$300,000
Orion mods assumed to only involve new equipment pallets, mounts, wiring, etc., (assume half of GH cost).		$150,000
Integration and test (assume half of GH cost).		$100,000
Flight test		$30,000
Science team total cost (8 scientists @ 160k per year each)		$640,000
Total Direct Costs (NASA rates)		**$2,774,000**

Table 3. Cost estimates of the Aurora Flight Sciences' Orion for Two Sensors from Edwards

Aurora Orion (1 sensor)

Cost Item	Value	Totals
Flight hour rate (estimate)	$1000	$720,000
Total fuel cost assumed included in hourly rate	$28,435	
Science data communications costs		$42,000
Project management/ requirements/ design/ planning (assume same as GH cost)		$300,000
Orion mods assumed to only involve new equipment pallets, mounts, wiring, etc., (assume half of GH cost).		$150,000
Integration and test (assume half of GH cost).		$100,000
Flight test		$30,000
Science team total cost (8 scientists @ 160k per year each)		$640,000
Total Direct Costs (NASA rates)		**$1,982,000**

Table 4. Cost estimates of the Aurora Flight Sciences' Orion for One Sensors from Edwards

6.3 DC-8

When calculating the mission total cost in table 5, the assumptions we made were a 6 month operational period, requiring 4 flights per month to cover the same ground as the Global Hawk, making a total of 24 flights for the campaign, carrying two sensors. The DC-8 has such large payload capability that only carrying one sensor does not significantly change the endurance. The total number of hours per flight is 12 which makes a total 288 hours total for the campaign. The DC-8 requires about 9,500 lbs of fuel per hour. The cost of fuel is calculated from the average fuel cost of Jet A fuel in the Edwards Air Force Base area in California. The costs for modifications, integration and test are less than Global Hawk, since interfaces and systems are designed in a modular way for ease of integration of payloads.

DC-8 (2 sensors)

Cost Item	Value	Totals
Flight hour rate (source 2015 NASA Call Letter)	$6,500	$1,872,000
Total fuel cost assumed included in hourly rate	$1,531,343	
Science data communications costs		$42,000
Project management/ requirements/ design/ planning (assume same as GH cost)		$300,000
DC-8 mods assumed to only involve new equipment pallets, mounts, wiring, etc., (assume half of GH cost).		$150,000
Integration and test (assume half of GH cost).		$100,000
Flight test		$30,000
Science team total cost (8 scientists @ 160k per year each)		$640,000
Total Direct Costs (NASA rates)		**$3,134,000**

Table 5. Cost estimates of the DC-8

7 Conclusion

Methane is potentially a significant contributor to climate change and there is insufficient knowledge about worldwide emissions. With this proposed methane monitoring mission, we will be better able

to understand how much methane can potentially be released into the atmosphere. Additionally, we will be able to further our calculations for the amount of methane hydrates trapped within the permafrost and better estimate the future impacts that global warming may cause. The proposed mission would be to initially use the Global Hawk based at Edwards and in the future, we propose that we could use Aurora Flight Sciences' Orion. The Orion may be more suitable for remote operations and is a better platform for taking accurate measurements due to it's slow cruise speed allowing long sensor integration times. Orion can carry both the LIDAR and infrared spectrometer Global Hawk only has sufficient payload capacity to carry one of these large sensors.

The proposed methane monitoring mission consists of six intensive observation campaigns in the northern high latitudes to quantify permafrost methane emission during the summer growing season. The Mackenzie Delta was identified as a potential sampling area where natural permafrost thaw signals are large and oil and gas exploration is active. A monthly sampling strategy is sufficient to capture seasonal variability. Long endurance UAS allow for observation of diurnal variability within the sampling area. Basing a team at a remote base near the site is not an efficient use of the UAS or personnel unless the methane measurement campaign can be combined with a campaign that does require frequent measurements, such as a cloud or ocean biology/ecology study. Flying out of Edwards is preferable, but requires a long transit to the site. The DC-8 does not have much endurance from Edwards, both Global Hawk and Aurora Orion have the required endurance to transit and remain on site for an extended period. Global Hawk has a much higher cruise speed that is advantageous for the transit and for operating in high winds. For the actual measurements the slow speed of Orion, however, would allow longer integration times leading to better accuracy. NASA experience with Global Hawk is that it is a very effective platform when long endurance/ distance is required, but it is relatively costly and does not have a good record of reliability for starting the mission. Once in flight it is very reliable. The use of the Global Hawk requires development of a radome and active cooling system to allow for implementation of the methane LIDAR system. The aircraft modifications would account for a large fraction of the total mission cost. Both sensors will likely require the use of the same space for operation on Global Hawk, thus making this platform not ideal for an active+passive mission concept. Aurora Orion may be considerably less costly to operate and, with an open architecture, may be easier and less expensive to modify. The option to buy time on Orion using a Contractor Owned Contractor Operated (COCO) business model may be attractive. Limitations of Orion are slow cruise speed and a lower altitude limit than Global Hawk. Future versions with turbocharged engines may be able to reach 50 kft or more and significantly higher speeds but with less endurance. Orion has the best endurance of any current operational UAV and is ideally suited for campaigns where fast cruise speeds and high altitudes are not required.

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14. ABSTRACT

Methane is likely to be an important contributor to global warming, and our current knowledge of its sources, distributions, and transport is insufficient. It is estimated that there could be anywhere from 7.5 to 400 billion tons of carbon-equivalent of methane in the arctic region, a broad range that is indicative of the uncertainty within the Earth Science community. Un-manned Air Vehicles (UAVs) are often used for combat or surveillance by the military, but they also have been used for Earth Science field missions. In this study, we will analyze the utility of the NASA Global Hawk and the Aurora Flight Sciences Orion UAVs compared to the manned DC-8 aircraft for conducting a methane monitoring mission. The mission will focus on measurement of methane along the boundaries of Arctic permafrost thaw and melting glaciers. The use of Long Endurance UAS brings a new range of possibilities including the ability to obtain a long-term and persistent observations and to significantly augment methane measurements/retrievals collected by satellite. Furthermore, we discuss the future of long endurance UAS and their potential for science applications in the next twenty to twenty-five years.

15. SUBJECT TERMS

Arctic; LIDAR; Methane; Permafrost; Remote sensing; UAV

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